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EMISSIVITY OF DEEP SEA HYDROTHERMAL VENT PLUMES

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Emissivity of deep sea hydrothermal vent plumes

A.J. Walton and G.T. Reynolds*

During the summer of 1999, discussions were held concerning the possibility of measuring the emissivity of hydrothermal vent plumes, involving A.J. Walton, G.T. Reynolds, S.N. White and A.D. Chave. The results of these discussions have been summarized by White. [1] The purpose of the report is to call attention to the subject as discussed by White and make more explicit the significance of determining the emissivity and possible means of measuring it.

The overall importance of vent study has been well stated in the preface to: Seafloor Hydrothermal Systems, AGU Geophysical Monograph 91 (1995) ed. S.E. Humphris, R.A. Zuremberg, L.S. Mullineau, and R.E. Thomson as follows:

“Hydrothermal circulation at mid-ocean ridges is one of the fundamental processes controlling the transfer of energy and matter from the interior of the Earth to the lithosphere, hydrosphere, and biosphere. Hydrothermal interactions influence the composition of the oceanic crust and the chemistry of the oceans. In addition, hydrothermal vent fields support diverse and unique biological communities by means of microbial populations that link the transfer of the chemical energy of dissolved chemical species to the production of organic carbon.”

Temperatures measured at the orifice of vent plumes commonly range from 300°K to 400°K. Thus, a considerable energy transfer from vent to surroundings is in the form of thermal radiation. It is useful to review the nature of this radiation and the properties of the vent plume that affect it.

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The fundamental equation for thermal radiation is the well-known Planck equation, which, modified for the case where the hot body is radiating into seawater of index of refraction n , takes the form:

$$N(\lambda)d\lambda = \frac{ecn^2}{\lambda^4} \left[\exp \left(\frac{hc}{\lambda kT} \right) - 1 \right]^{-1} d\lambda \quad (1)$$

where c is the velocity of light in vacuum, h is Planck's constant, k is Boltzmann's constant, T is temperature in degrees Kelvin and $N(\lambda)d\lambda$ is the number of photons emitted per second into unit solid angle between the wavelengths λ and $\lambda + d\lambda$ per square meter of source of emissivity e .

All of the terms in the above equation are well known or can easily be determined except for the emissivity e , defined as follows:

Emissive power: The energy radiated from unit area of a surface in unit time per unit difference in temperature between the radiating body and its surroundings.

Emissivity: The ratio of the emissive power of a body to that of a perfect blackbody i.e., a body that absorbs all of the energy incident on it, and whose emissivity $e = 1$.

The emissivity of vent plumes is uncertain and remains to be measured. In early estimates of thermal radiation from vents it was taken to be 0.3. [2] However, although this seemed to fit the available data fairly well, it was little better than an "educated guess". In subsequent observations of flange pools, where there was no precipitation or turbulence, a reasonable value appeared to be 0.9. [1].

For a basic presentation of the thermodynamic role of emissivity and Kirchoff's Law, reference can be made to any standard text [3,4]. Kirchoff's law states that the ratio of the emissive power to the absorption power of a body depends only on the temperature of the body and not on its nature. To continue it is useful to define absorptive power: the fraction of the incident radiation that is absorbed in the body.

In some of the literature, statements are made of Kirchoff's law that utilize "emissive coefficient" or "absorptive coefficient" and Kirchoff's law is stated in terms of these coefficients. However, our interest is on the amount of energy absorbed by the body, which

depends on the thickness. In addition, all of these quantities depend on wavelength as well as temperature. A key point in the discussions of blackbody radiation is that there is thermal equilibrium. However, the case of vents (and in fact all "real" situations) necessarily involve some departure from complete equilibrium. Even so, we will treat the problem as an approximation to equilibrium conditions. [5]

It is useful to refer first to the work of McMahon. The analysis is applied to a sheet of material that is partially reflecting and partially transparent. A conventional measurement of reflectivity gives what he terms the "apparent reflectivity" designated as R^* . A similar measurement of transmissivity gives what McMahon terms the "apparent transmissivity", T^* . Because of repeated reflections of the light between the surfaces of the sheet, the "true reflectivity", R , and "true transmissivity", T are less than the corresponding apparent values, and the relationships are obtained by summing the appropriate series (note R and T are < 1). The measurable quantities are R^* and T^* . The relationship of the true values to the apparent values are given as:

$$R^* (\lambda, t) = R(\lambda, t) \left[1 + \frac{T^2(\lambda, t)\{1 - R(\lambda, t)\}^2}{1 - R^2(\lambda, t) \cdot T^2(\lambda, t)} \right]$$

$$T^* (\lambda, t) = T(\lambda, t) \left[\frac{\{1 - R(\lambda, t)\}^2}{1 - R^2(\lambda, t) \cdot T^2(\lambda, t)} \right]$$

where λ is the wavelength and t is the absolute temperature. The emissivity, E , is given by:

$$E (\lambda, t) = \frac{\{1 - R(\lambda, t)\}\{1 - T(\lambda, t)\}}{\{1 - R(\lambda, t) \cdot T(\lambda, t)\}}$$

Algebraically, the sum of all three equations is:

$$E(\lambda, t) + R^* (\lambda, t) + T^*(\lambda, t) = 1$$

The relations may be tested for various special cases: for example, a complete opaque body, for which

$$E(\lambda, t) = \{1 - R(\lambda, t)\}$$

a form of Kirchoff's law for this special case.

McMahon provides a triangular coordinate chart representing the solution of the three equations of E , R^* , and T^* in terms of R and T . The properties of a particular body at a given wavelength and temperature are represented by a single point on the chart. Nicodemus [5] supplies the same chart, more completely labeled, shown in Figure 1. The notation is $E = \epsilon$, $T^* = \tau$, and $R^* = \rho$. Thus, a measurement of $R^* = 0.35$ and $T^* = 0.35$ would lead to the conclusion $E = 0.30$; as would many other combinations, such as a measurement of $R^* = .20$, $T^* = 0.5$. This seems straight forward, but two parameters have been neglected.

1) The plume is more cylindrical than sheet-like. 2) There is scattering in the plume. [7]

In the laboratory, design of experiments to take these into account would not be complicated. However, in a real deep-sea environment, the realization of the experiment would be difficult. In principal, one can sketch the following procedure [1].

- i) From existing data for emission at 800 nm, 900 nm, 1000 nm fit a blackbody curve for the measured temperature.
- ii) Extrapolate the fitted curve to the region 400-600 nm.
- iii) Based on this curve choose a light source (laser) ~ 100 times as bright as the blackbody value.
- iv) Using this light source, measure the apparent reflectivity R^* and apparent transmissivity T^* , as in Figure 2 [1].
- v) Measure the scattered light S^* , as in Figure 3 and Figure 4 [1]. Obtain the estimate of emission from the amended McMahon equation

$$E = 1 - R^* - T^* - S^* .$$

This is, of course, valid for only the wavelength used, but with relatively unlimited resources it could be repeated for several wavelengths. It is possible that the wavelength dependence of emissivity in the range of interest is not great. In any case, the estimate of E will be better than those made so far.

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Figure Captions

Figure 1 Thermal radiation chart for semitransparent media. ϵ , τ , and ρ are emissivity, apparent transmissivity and apparent reflectivity, respectively.

Figure 2 Measurement of apparent reflectivity and transmissivity (of a slab) by means of a strong collimated radiation source J .

Figures 3 & 4 Measurements designed to detect scattered light from the plume.

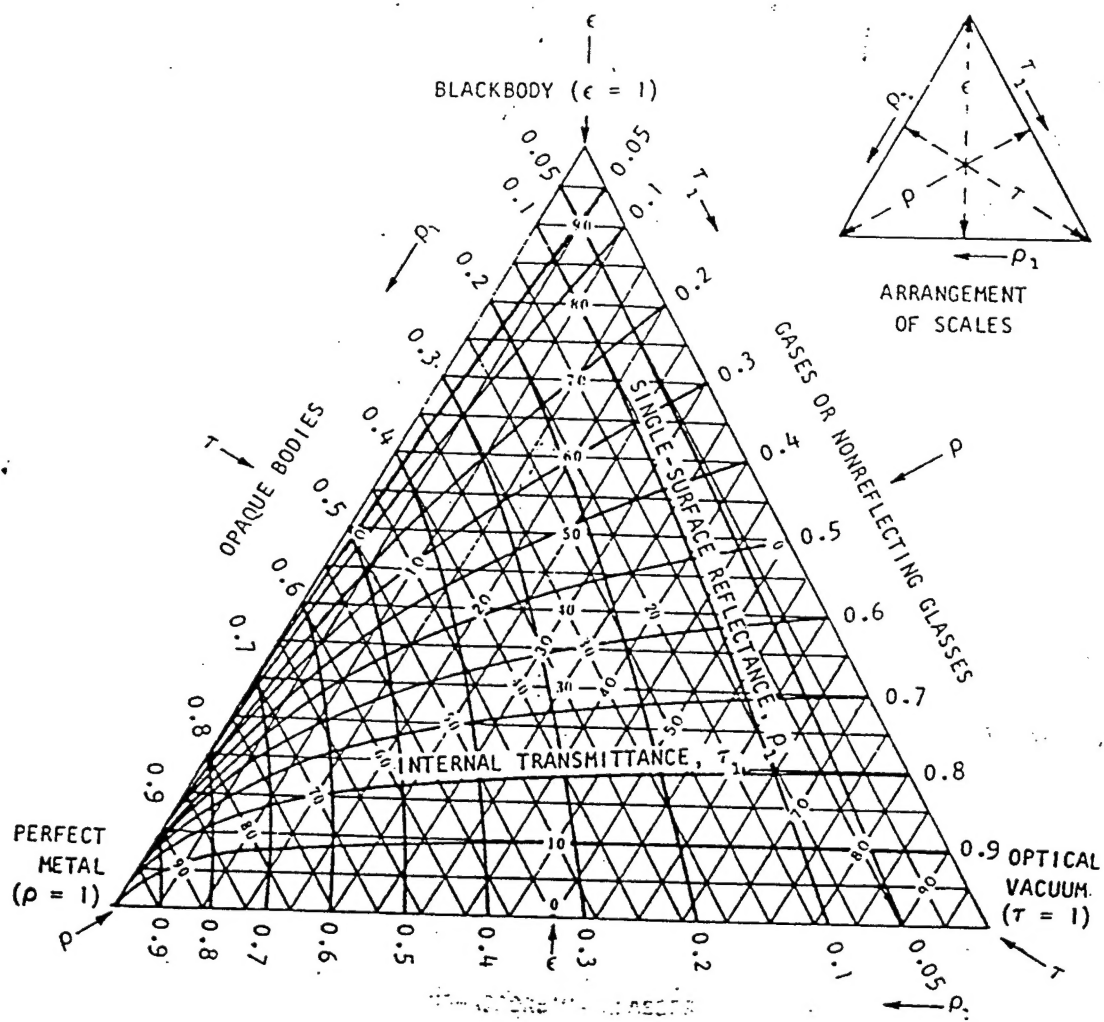


Figure 1

Reflectivity $R^* = \frac{J_r}{J_i}$
 Transmissivity $T^* = \frac{J_t}{J_i}$
 Absorptivity $A = \frac{J_a}{J_i}$
 Emissivity $E = A = 1 - R^* - T^*$

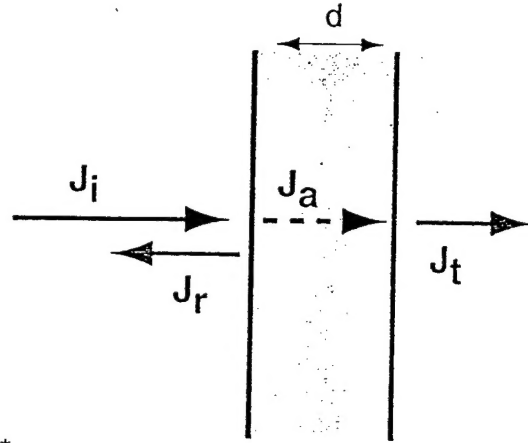


Figure 2

Scattered Light
 $J_s = J_{s1} + J_{s2} + J_{s3}$
 $S^* = \frac{J_s}{J_i}$
 Emissivity
 $E = 1 - R^* - T^* - S^*$

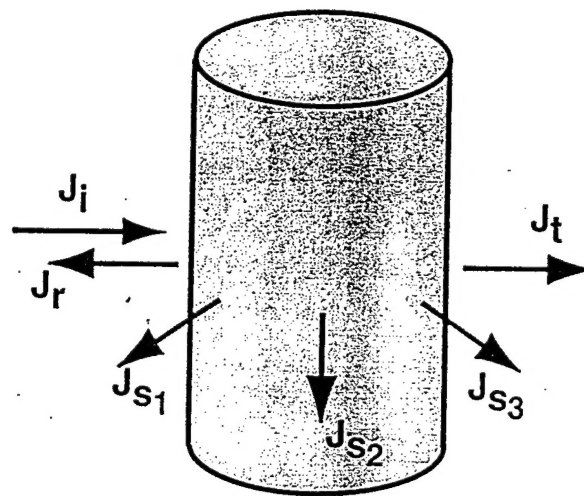


Figure 3

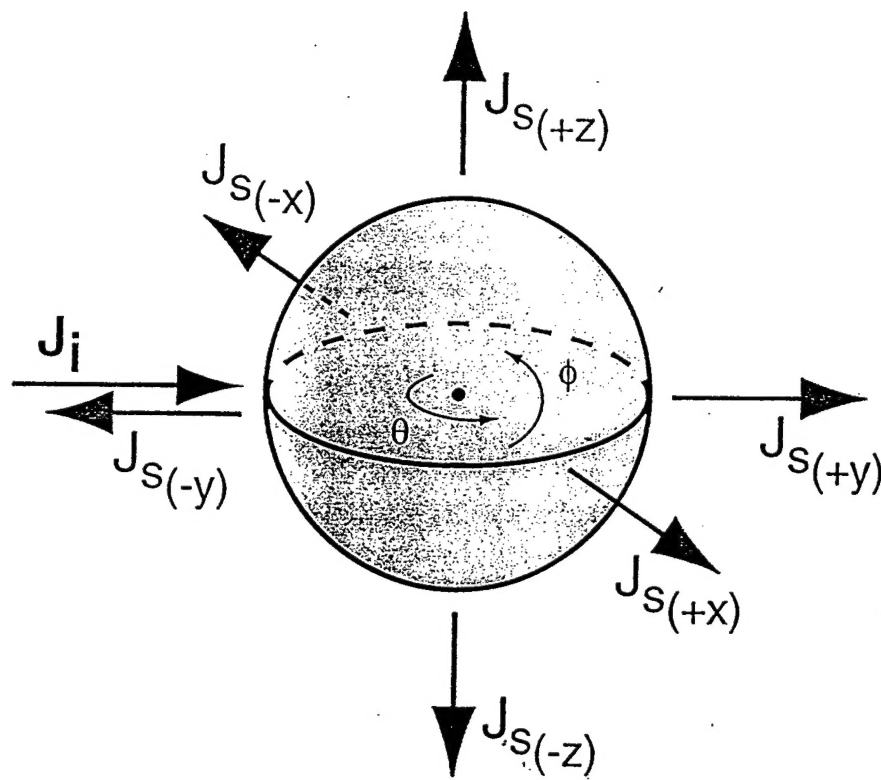


Figure 4

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